Golden Obsessions: Identifying the Higgs Through the Golden Channel

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(Supported by Fermilab Graduate Student Fellowship)

HEP Seminar: Fermilab
August 22, 2013

Daniel Stolarski, RVM: arXiv:1208.4840 and Y. Chen, Nhan Tran, RVM: arXiv:1211.1959

Yi Chen, Kunal Kumar, Shashank Shalgar, RVM: in preparation

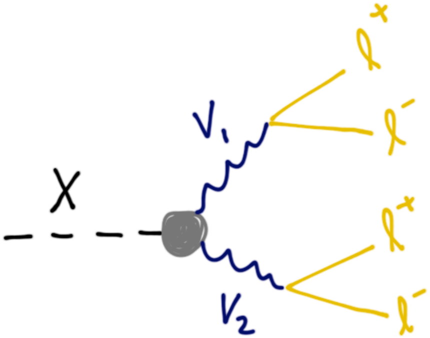
Yi Chen, Emanuele DiMarco, Joe Lykken, Maria Spiropulu, RVM, Si Xie: in preparation

Overview

- What is the Golden Channel?
- Why the Golden Channel?
- Experimental Searches
- Constructing Likelihood Analysis
- Extracting Higgs Couplings
- Including Detector Effects
- Ongoing/Future Studies
- Conclusions

What is the Golden Channel?: Signal

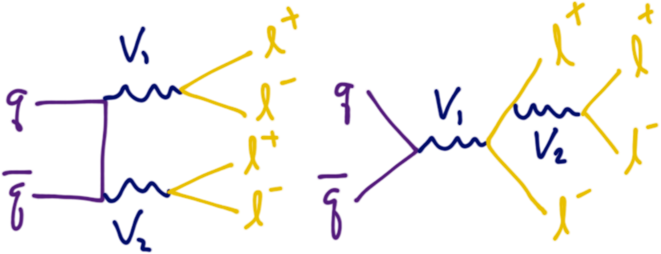
- Signal consists of $\varphi \to V_1 V_2 \to 4\ell$



- X can in principal be spin 0, 1, or 2
- V_1 and V_2 can be any combination of Z and γ and $\ell = e, \mu$
- In principal $\gamma\gamma$, $Z\gamma$, and ZZ all contribute
- Can lead to a myriad of interference effects between intermediate states as well as between identical final states in $4e/4\mu$ channel

What is the Golden Channel?: Background

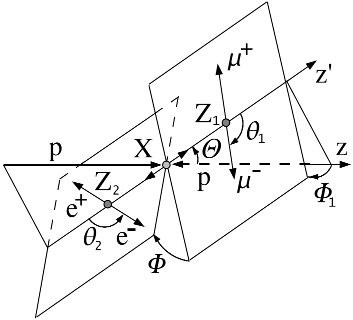
- Irreducible background is primarily $q\bar{q} \to 4\ell$
- This includes both the t-channel and s-channel process



- Also has smaller contribution from fakes and $gg \to 4\ell$ (NLO)
- Again V_1 and V_2 can be Z or γ and $\ell = e, \mu$
- A rich interference structure between various intermediate states as well as between s and t-channel and identical final states for $4e/4\mu$

What is the Golden Channel?: Kinematics

- Ignoring production there are 8 observables in CM frame per event $(s, M_1, M_2, \Theta, \theta_1, \theta_2, \Phi_1, \Phi)$ (N. Cabibbo, A. Maksymowicz, Phys. Rev. 137 (1968))



(Y. Chen, N. Tran, RVM: 1211.1959)

- All angles defined in 4ℓ CM frame (or X in case of signal)
- Correlations between lepton angles studied for some time

J.F. Gunion, Z. Kunszt (1986); Matsurra, J.J. Van Der Bij (1991), + many others

Why the Golden Channel?: 'Practical' Reasons

- Very well measured with $\lesssim 1-2\%$ mass resolution for ~ 125 GeV
- Good signal to background ratio and well understood theoretically
- NLO corrections are small and mainly affect production
- Make it conducive to 'analytic' methods based on LO calculation
- Analyzed recently using matrix element method (MEM) studies

Y. Gao, A. V. Gritsan, Z. Guo, K. Melnikov, M. Schulze, et. al: **1001.3396**
A. De Rujula, J. Lykken, M. Pierini, C. Rogan, M. Spiropulu: **1001.5300**
J. Gainer, K. Kumar, I. Low, RVM: **1108.2274**
S. Bolognesi, Y. Gao, A. V. Gritsan, K. Melnikov, et. al: **1208.4018**
D. Stolarski, RVM: **1208.4840**
Avery, Bourilkov, Chen, Cheng, Drozdetskiy, et. al: **1210.0896**
J.M. Cambell, W.T. Giele, C. Williams (NLO): **1205.3434**
J.M. Cambell, W.T. Giele, C. Williams (NLO): **1204.4424**

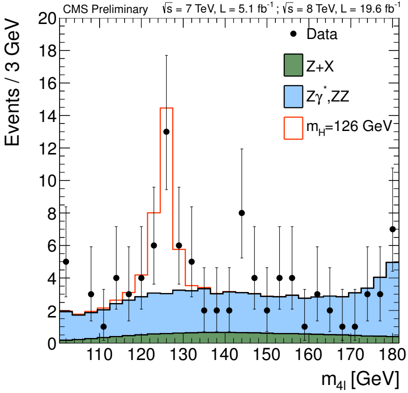
- Focused primarily on signal extraction and/or hypothesis testing
- We would like to move on to direct parameter extraction

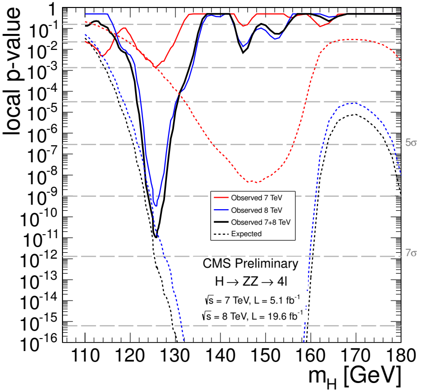
Why the Golden Channel?: Physics Reasons

- Can be used as a 'discovery' mode as done for Higgs
- Can directly test EWSB mechanism
- Can measure spin of resonance directly
- Direct probe of CP properties and can be used to extract phases
- $Z\gamma$ and $\gamma\gamma$ occur through higher dim operators $\Rightarrow$ sensitive to NP

Experimental Searches

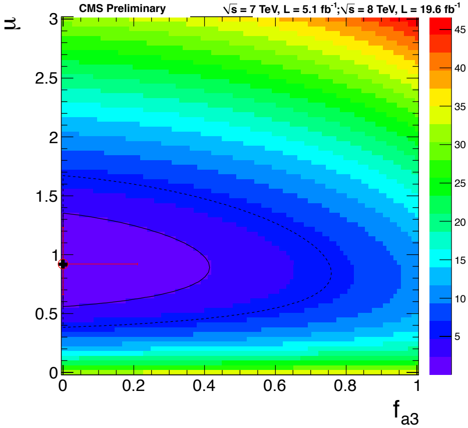
- The Higgs has been discovered in the Golden Channel at $\sim$ 125 GeV!





- Experiments have now entered 'characterization phase'

- CMS has also performed studies of CP mixtures
- Assessing sensitivity to real *CP*-odd *ZZ* coupling



- Some CP odd/even mixtures still allowed
- Could there be phases?

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- Build an analysis framework to fully utilize the power of the golden channel in a model independent manner which takes into account detector effects and systematic uncertainties

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- Utilizing all 8 possible decay observables in minimal computing time
- Directly extract the Higgs couplings (ratios of couplings) to neutral electroweak gauge bosons in the golden channel final state

Constructing a likelihood analysis

- A likelihood can be formed out of probability density functions (*pdfs*) using full set of decay observables in golden channel

$$L(\vec{\lambda}) = \prod_{\mathcal{O}}^{N} \mathcal{P}(\mathcal{O}|\vec{\lambda})$$

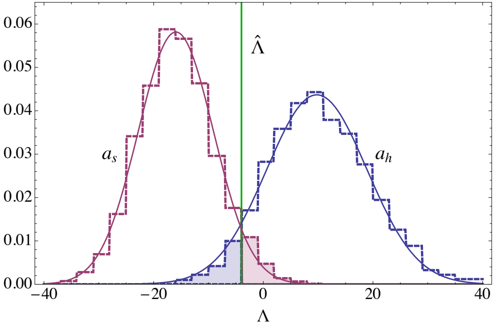
$$\mathcal{O} = (s, M_1, M_2, \vec{\Omega})$$

- $\mathcal{P}(\mathcal{O}|\vec{\lambda})$ built out of fully differential cross section for CM observables
- It takes in the set of CM observables $\mathcal{O}$ as input
- $L(\vec{\lambda})$ a function of lagrangian parameters
- Gives the likelihood for observing a given data set (N events of $\mathcal{O}$)

Simple Hypothesis Test

- Can use likelihood to construct ratios to do simple hypothesis testing
- Useful for signal from BG extraction and exclusion in favor of SM

$$\Lambda = L(\lambda_a)/L(\lambda_b) \longrightarrow \sigma$$



(D. Stolarski, RVM: 1208.4840)

Parameter Extraction

- Instead of hypothesis testing one can also do parameter extraction
- This is done by maximizing the likelihood with respect to $\vec{\lambda}$

$$\frac{\partial L(\vec{\lambda})}{\partial \vec{\lambda}}\bigg|_{\hat{\lambda}} = 0$$

- For a single experiment of N events $\hat{\lambda}$ gives the value of the parameter which maximizes the likelihood
- This is repeated for a large set of $\mathcal{N}$ pseudo-experiments and one obtains a distribution for $\hat{\lambda}$ with a given spread and average value $\hat{\lambda}_{avg}$
- The true value $\vec{\lambda}_o$ will sit in some interval around $\hat{\lambda}_{avg}$
- In the limit as $\mathcal{N} \to \infty$ one will find $\hat{\lambda}_{avg} \to \vec{\lambda}_o$

Signal *pdf*

- The signal *pdf* is formed out of fully differential cross section for $h \to V_1 V_2 \to 4\ell$ where $4\ell = 2e2\mu, 4e, 4\mu$ and $V_{1,2} = Z, \gamma$

$$\mathcal{P}_S(m_h^2, M_1, M_2, \vec{\Omega}|\vec{\lambda}) = \frac{d\sigma_{h\to 4\ell}}{dM_1^2 dM_2^2 d\vec{\Omega}}$$

- Can also contain production spectrum for $\vec{p}_T$ and Y
- Many possible couplings between Higgs and neutral gauge boson pairs
- We assume only Lorentz invariance between a spin-0 scalar and vector boson pairs and allow for general CP mixtures and phases
- Would like to directly extract as many of the parameters as possible (even if they are zero)

Scalar Signal Parametrization

- Parametrize scalar couplings to vector boson pairs as the following,

$$\Gamma_{ij}^{\mu\nu}(k,k') = \frac{1}{v}\Big(A_{1ij} m_Z^2 g^{\mu\nu} + A_{2ij}\left(k^\nu k'^\mu - k\cdot k' g^{\mu\nu}\right) + A_{3ij}\epsilon^{\mu\nu\alpha\beta} k_\alpha k'_{2\beta}\Big)$$

- The A_{nij} in principal complex and $ij = ZZ, Z\gamma, \gamma\gamma$ ($A_{1Z\gamma} = A_{1\gamma\gamma} = 0$)
- k, k' momentum of vector bosons (or lepton pair system)
- Can for example be derived from the following Lagrangian,

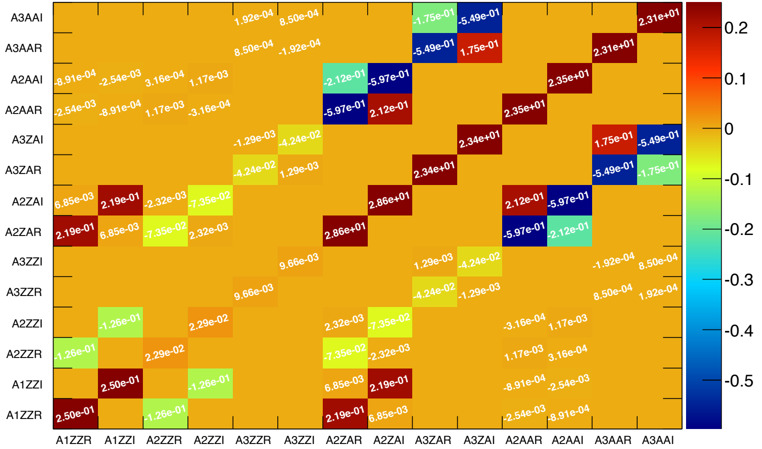
$$\begin{aligned}\mathcal{L} \sim \frac{1}{v}\varphi\Big(& g_h m_Z^2 Z^\mu Z_\mu + g_Z Z^{\mu\nu} Z_{\mu\nu} + \tilde{g}_Z Z^{\mu\nu}\widetilde{Z}_{\mu\nu} \\ &+ g_{Z\gamma} F^{\mu\nu} Z_{\mu\nu} + \tilde{g}_{Z\gamma} F^{\mu\nu}\widetilde{Z}_{\mu\nu} \\ &+ g_\gamma F^{\mu\nu} F_{\mu\nu} + \tilde{g}_\gamma F^{\mu\nu}\widetilde{F}_{\mu\nu} + \ldots\Big)\end{aligned}$$

- All operators included in our calculation to form signal *pdf*
- In differential cross section, pairs of operators will form 'partial widths'
- Depending on interference effects between vertex structures (or operators) some of these can be negative

'Relative widths' for Pairs of Scalar Couplings: $2e2\mu$

- Can form relative widths (to the SM) to examine 'branching fractions'

'Loose Cuts', 125 GeV, All $A_{nij} = 1$

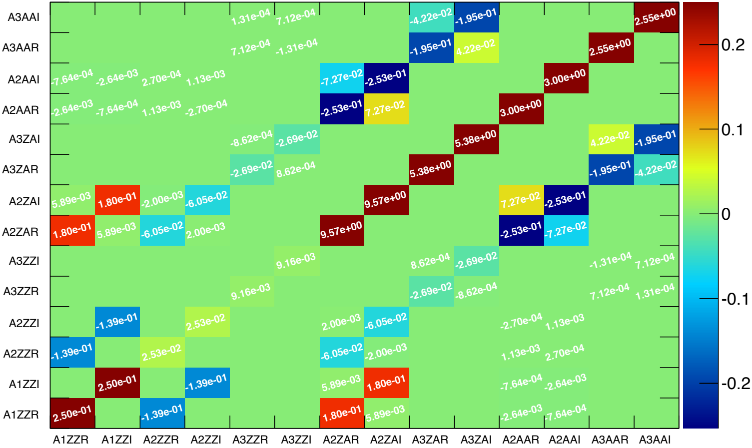


Preliminary

'Relative widths' with CMS Cuts: $2e2\mu$

- Will of course be different for different cuts

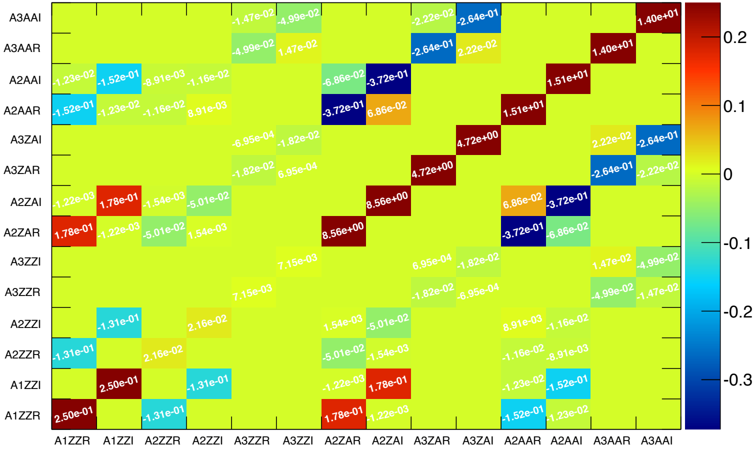
'CMS Cuts', 125 GeV, All $A_{nij} = 1$



Preliminary

- As well as between $2e2\mu$ and $4e/4\mu$

'CMS Cuts', 125 GeV, All $A_{nij} = 1$



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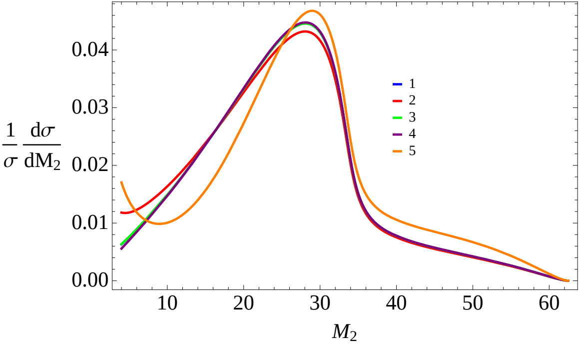
M_2 Distribution ($2e2\mu$)

- Of course we have shapes to aid us as well



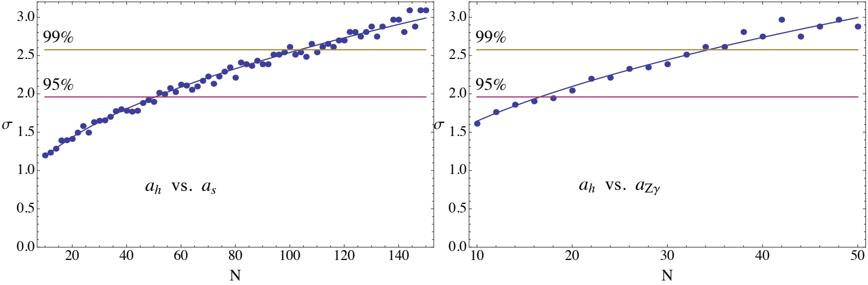
(Y. Chen, N. Tran, RVM:1211.1959)

- Slope of M_2 as upper cutoff is approached contains information about CP properties R. Boughezal, T. LeCompte, Petriello: **1208.4311**
- How phase space is chosen affects sensitivity to various couplings

'Relative differential Widths' as Discriminators: $2e2\mu$

- Use all decay observables $\mathcal{O}$ and assuming pure signal sample
- Simple hypothesis test to assess ability to distinguish operators
- For example, $Z_\mu Z^\mu$, $Z^{\mu\nu} Z_{\mu\nu}$, and $Z^{\mu\nu} F_{\mu\nu}$ (couplings set to one)

(D. Stolarski, RVM: 1208.4840)

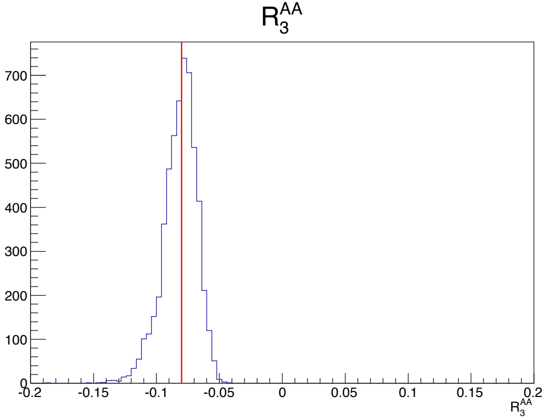


- Golden channel can distinguish $Z_\mu Z^\mu \& Z^{\mu\nu} Z_{\mu\nu}$ with $\mathcal{O}(40)$ events
- Can distinguish $Z_\mu Z^\mu \& Z^{\mu\nu} F_{\mu\nu}$ with $\mathcal{O}(20)$ events

Simple Parameter Extraction: Signal Only

- Instead of hypothesis testing, now we do direct parameter extraction
- Perform a 6 parameter fit for all couplings assuming all real

1k Events, 5k Pseudo Experiments, $R_n^{ij} = A_{nij}/A_{1ZZ}$



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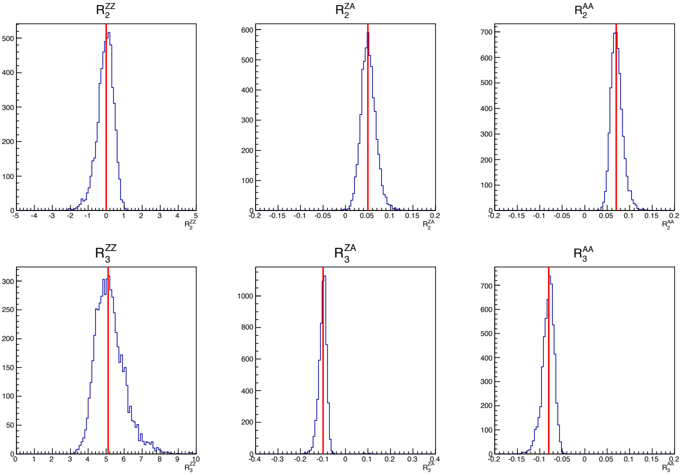
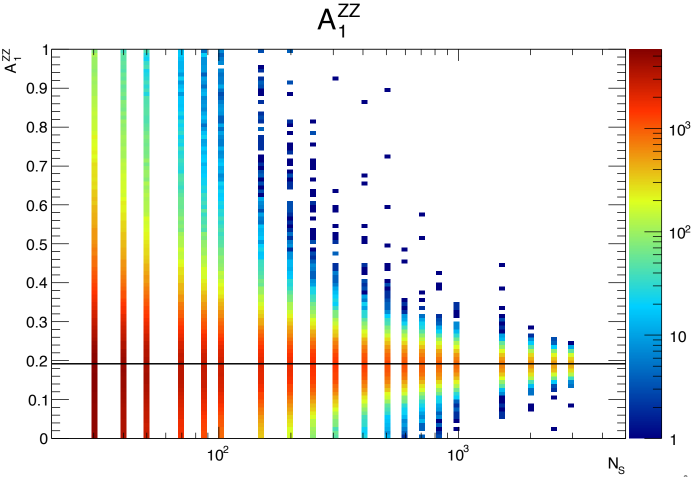


Preliminary

- We can see how fit error changes with number of events

N = 30 to 3000 Events per Pseudo Experiment



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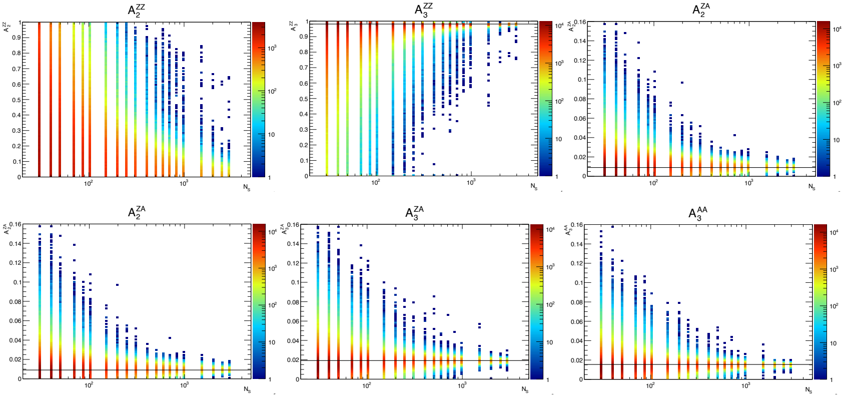

Preliminary

Simple Parameter Extraction: Signal Only

- Can also examine correlations between parameters

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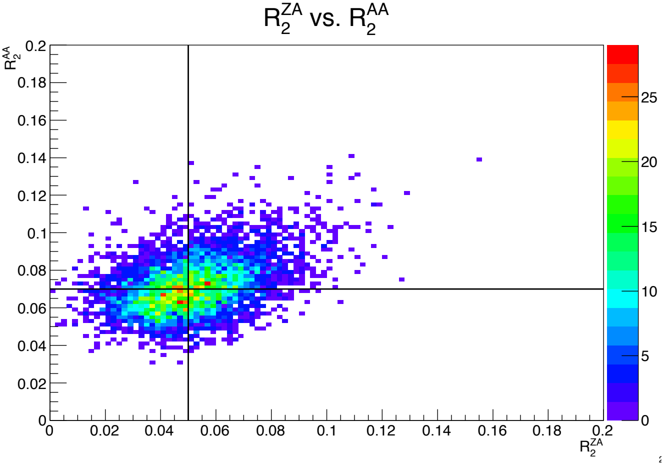

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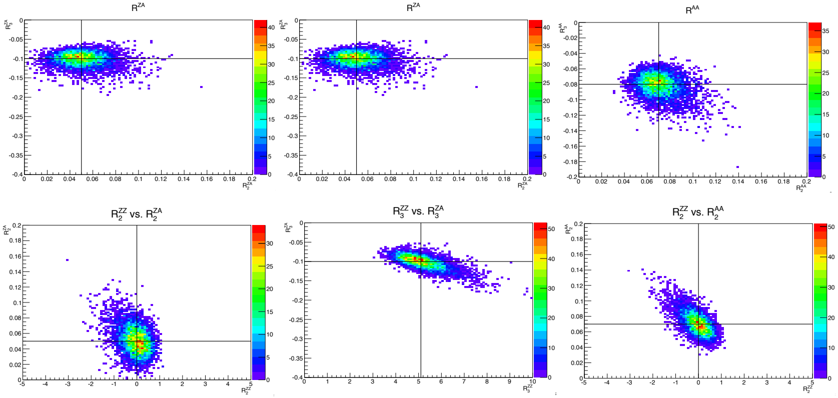


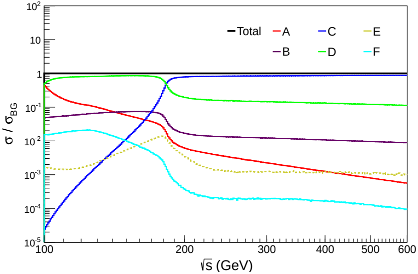
Preliminary

Background *pdf*

- The leading order irreducible background *pdf* is formed out of fully differential cross section for $q\bar{q} \to 4\ell$

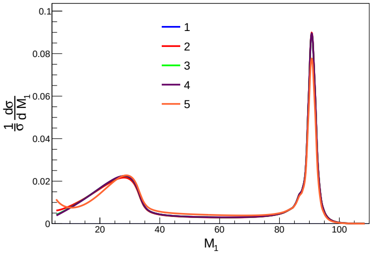
$$\mathcal{P}_B(s, M_1, M_2, \vec{\Omega}) = \frac{d\sigma_{q\bar{q}\to 4\ell}}{dM_1^2 dM_2^2 d\vec{\Omega}}$$

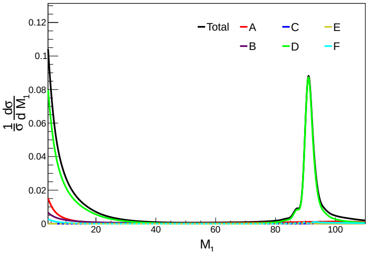
- Will discuss production $W(s, \vec{p}_T, Y)$ spectrum later
- BG composed of mostly $Z\gamma$ $t - channel$

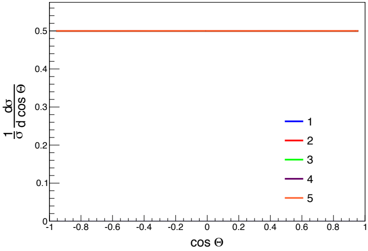


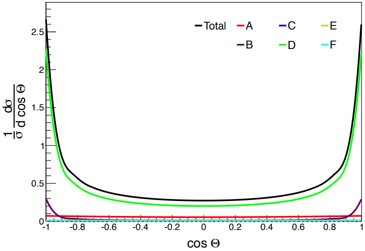
- Shapes are strong discriminator between signal and background

- $M_{1,2}$ and $\cos\Theta$ differential spectrums **Y. Chen, N. Tran, RVM: 1211.1959**

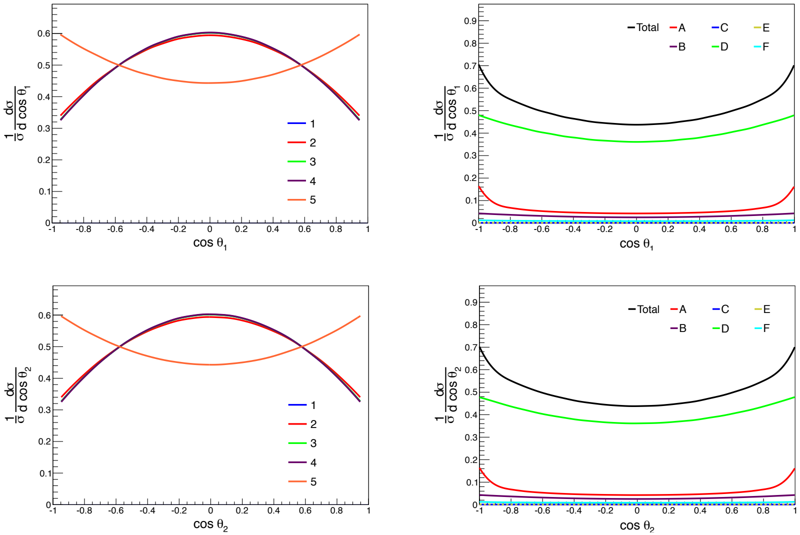






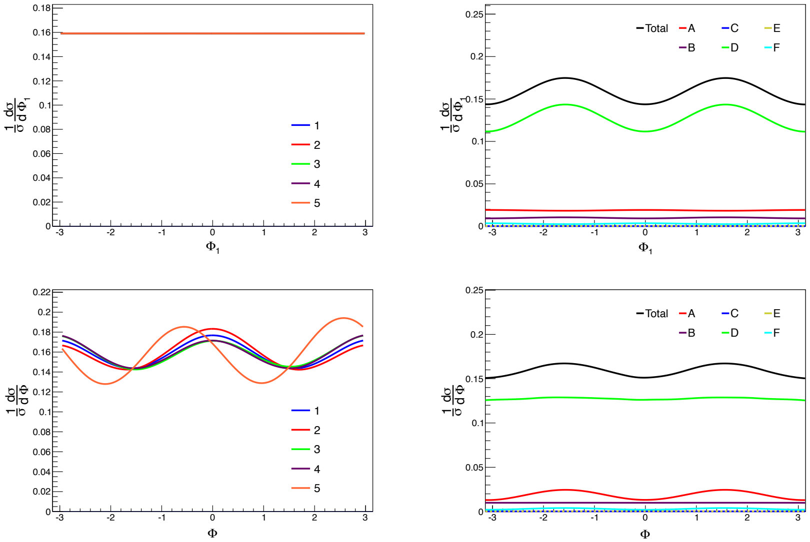


- $\cos\theta_{1,2}$ differential spectrums **Y. Chen, N. Tran, RVM: 1211.1959**



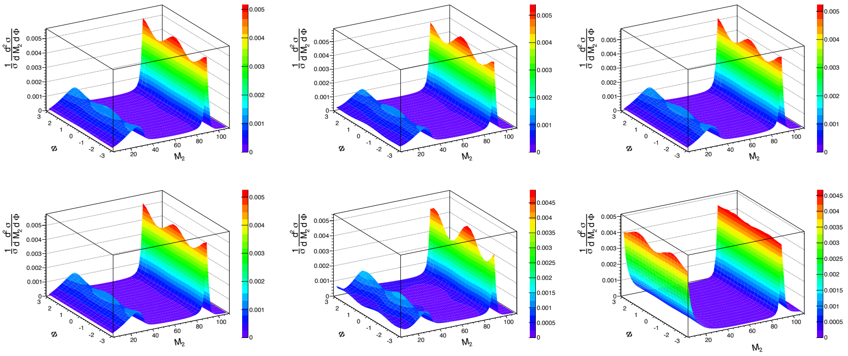
Golden Channel: Sig vs BG Distributions ($2e2\mu$)

- Φ_1 and Φ differential spectrums **Y. Chen, N. Tran, RVM: 1211.1959**



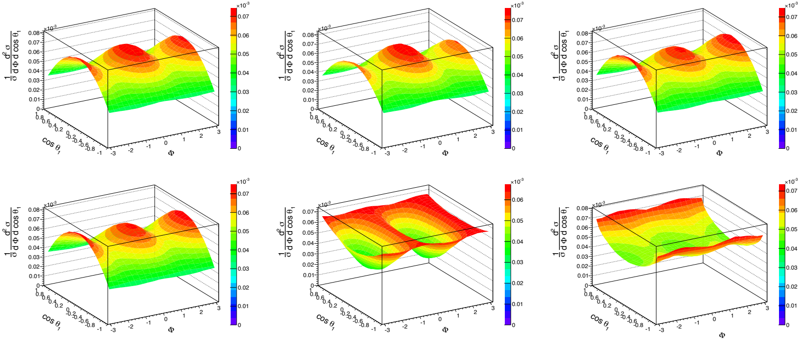
Golden Channel: Sig vs BG Distributions ($2e2\mu$)

- $(M_{1,2}, \Phi)$ doubly differential spectrums **Y. Chen, N. Tran, RVM: 1211.1959**



Golden Channel: Sig vs BG Distributions ($2e2\mu$)

- $(\cos\theta_{1,2}, \Phi)$ doubly differential spectrum **Y. Chen, N. Tran, RVM: 1211.1959**



- Of course projections don't show correlations contained in fully diff cxn
- Working on animations for webpage (soon to be public)

Signal + Background Likelihood

- Can now form signal plus background likelihood

$$L(f,\vec{\lambda}) = \prod_{\mathcal{O}}^{N} \mathcal{P}_{S+B}(\mathcal{O}|f,\vec{\lambda})$$

- With signal plus background

$$\mathcal{P}_{S+B}(\mathcal{O}|f,\vec{\lambda}) = f \times \mathcal{P}_B(s, M_1, M_2, \vec{\Omega})$$
$$+(1-f) \times \mathcal{P}_S(m_h^2, M_1, M_2, \vec{\Omega}|\vec{\lambda})$$

- Likelihood now function of background fraction f in addition to $\vec{\lambda}$
- Can now easily perform fits for $\vec{\lambda}$ and f

'Detector level' Likelihood

- Ideally one also wants to include detector effects in likelihood
- Need a likelihood that takes *reconstructed* CM observables as input
- This can be done by a convolution of the generator level *pdf* with a transfer function $T(\vec{X}^R|\vec{X}^G)$ over generator level observables

$$P(\vec{X}^{\mathrm{R}}|\vec{\lambda}) = \int P(\vec{X}^{\mathrm{G}}|\vec{\lambda}) T(\vec{X}^R|\vec{X}^G) d\vec{X}^{\mathrm{G}}$$

- $T(\vec{X}^R|\vec{X}^G)$ represents probability to observe $\vec{X}^R$ given $\vec{X}^G$
- We assume transfer functions of leptons are independent
- This integration takes us from generator level ($\vec{X}^G$) observables to reconstructed detector level observables ($\vec{X}^R$)
- Conceptually simple, but requires a number of steps to perform (and massive computing) see technical note for details
- Have performed this convolution for both signal and background

Normalization and Averaging over Y, p_T

- We then average over reconstructed p_T, Y and do not include them as observables in likelihood

$$P(s, M_1, M_2, \vec{\Omega}) = \int P(\vec{X}) dY d\mathbf{p}_T$$

(where we implicitly use only reconstructed observables from now on)

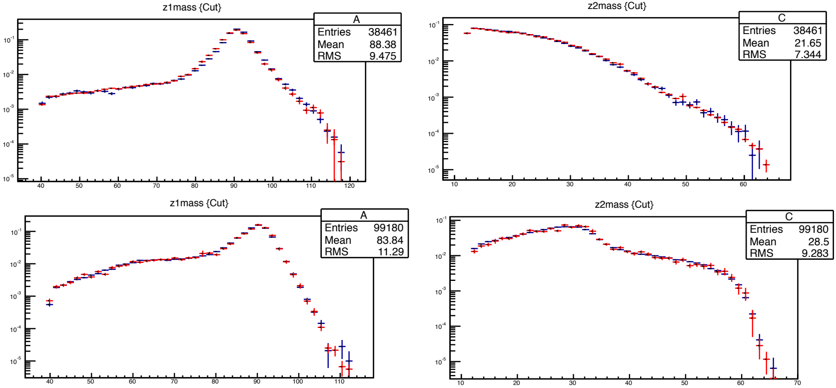
- Need overall normalization of *pdf* for detector level decay observables

$$\mathcal{N} = \int P(s, M_1, M_2, \vec{\Omega})$$
$$\times\, ds dM_1^2 dM_2^2 d\vec{\Omega}$$

$$\mathcal{P}(s, M_1, M_2, \vec{\Omega}) = \mathcal{N}^{-1} \times P(s, M_1, M_2, \vec{\Omega})$$

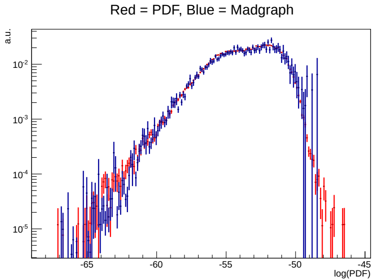
- Can be obtained via Monte Carlo integration see technical note for details
- Now have all pieces necessary for detector level likelihood $L_R(\vec{\lambda})$
- Can perform fits in the same manner as in the generator level studies
- Once $L_R(\vec{\lambda})$ is constructed fits to parameters are very fast

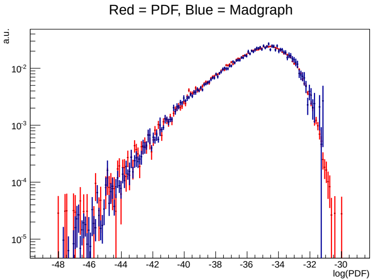
- We plot our detector level projections (red) on top of Madgraph data which has had detector effects applied to it (blue)



Preliminary

- We can do the same thing with the likelihoods





Preliminary

- These are the detector level likelihoods

Summary of Analysis Procedure

Direct Extraction of Higgs Couplings in Golden Channel

- Obtain analytic generator level pdf $P(\vec{X}^G|\vec{\lambda})$ from fully diff cxn
- Perform convolution with transfer function

$$P(\vec{X}^{\mathrm{R}}|\vec{\lambda}) = \int P(\vec{X}^{\mathrm{G}}|\vec{\lambda})T(\vec{X}^R|\vec{X}^G)d\vec{X}^{\mathrm{G}}$$

- Normalize *pdf* over $\vec{X}^R$, build detector level likelihood as function of $\vec{\lambda}$

$$L(\vec{\lambda}) = \prod_{\vec{X}^R}^{N} \mathcal{P}(\vec{X}^R|\vec{\lambda})$$

- Maximize likelihood with respect to undetermined parameters

$$\frac{\partial L(\vec{\lambda})}{\partial \vec{\lambda}}\Big|_{\hat{\lambda}} = 0$$

- Extract $\hat{\lambda}$ for a given data set of N observables

Ongoing Work/Down the Road

- Things left to Implement/Optimize:
  - Optimization of convolution especially for signal *pdf*
  - Optimization of production effects
  - Inclusion of systematic uncertainties
  - Strategy for performing fits and optimal parametrization
- Once framework is sufficiently optimized:
  - Perform detailed study of Higgs ZZ couplings assuming near SM
  - Perform a dedicated study of $Z\gamma$ and $\gamma\gamma$ couplings
  - Perform detailed comparison of $2e2\mu$ vs $4e/4\mu$ channels
  - Apply analysis framework to study $h \to 2\ell\gamma$ channel
  - Extract Higgs couplings!

Conclusion

- Golden Channel indispensable window to underlying physics
- NP could show up in small deviations of the kinematic distributions
- We have built a continuous, detector level, likelihood to maximize the information contained in this channel
- We utilize all 8 reconstructed Higgs CM decay observables
- Can perform direct multi-parameter extraction to pin down Higgs couplings to neutral EW gauge bosons including correlations
- An amazing channel containing vast information and which should be carefully studied from all angles

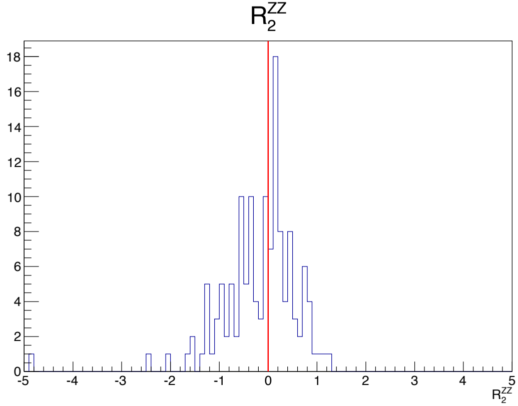
Conclusion

- Golden Channel indispensable window to underlying physics
- NP could show up in small deviations of the kinematic distributions
- We have built a continuous, detector level, likelihood to maximize the information contained in this channel
- We utilize all 8 reconstructed Higgs CM decay observables
- Can perform direct multi-parameter extraction to pin down Higgs couplings to neutral EW gauge bosons including correlations
- An amazing channel containing vast information and which should be carefully studied from all angles
- Thank you to Fermilab Graduate Student Fellowship program!

- Perform a 6 parameter fit for all A_{2ij}, A_{3ij} assuming SM

100 Signal + 25 Background Events, 130 Pseudo Exp

$$R_n^{ij} = A_{nij}/A_{1ZZ}$$



Preliminary

Extra Slides: Detector Level Signal + Background

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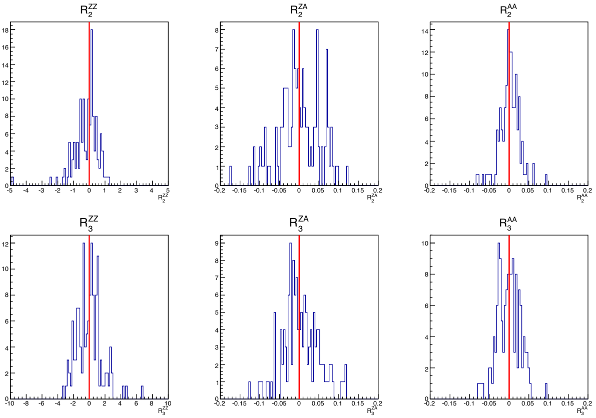
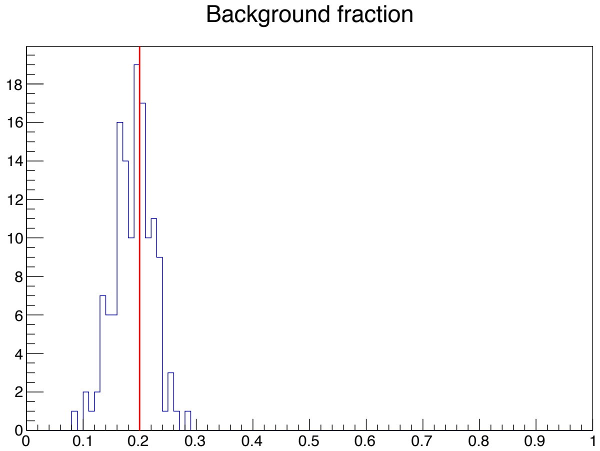


Preliminary

Extra Slides: Detector Level Signal + Background

- We must now also fit to the background fraction

100 Signal + 25 Background Events, 130 Pseudo Exp



Preliminary

- Can also examine correlations between parameters

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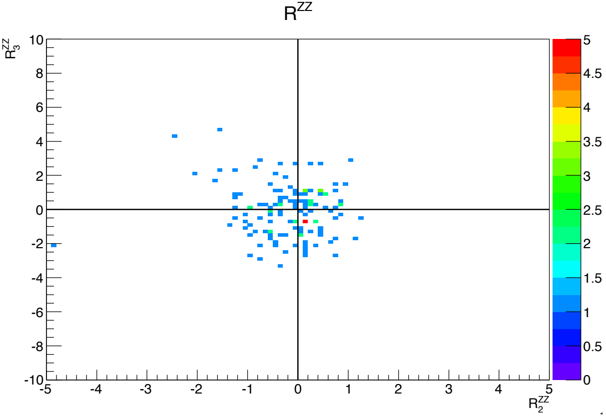

Preliminary

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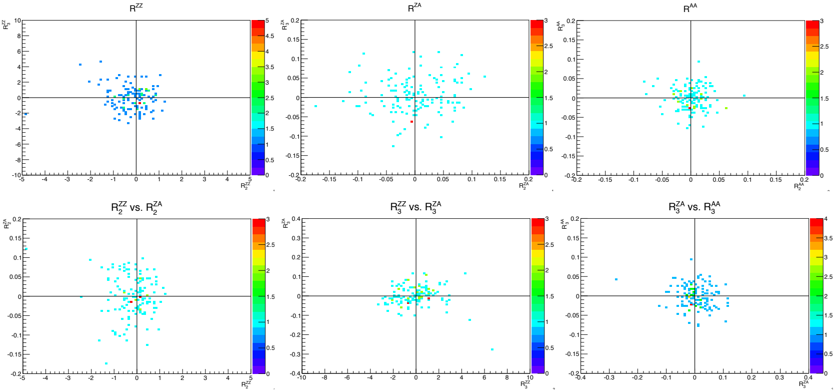


Preliminary

Extra Slides: 'Absolute Branching Ratios' - $2e2\mu$

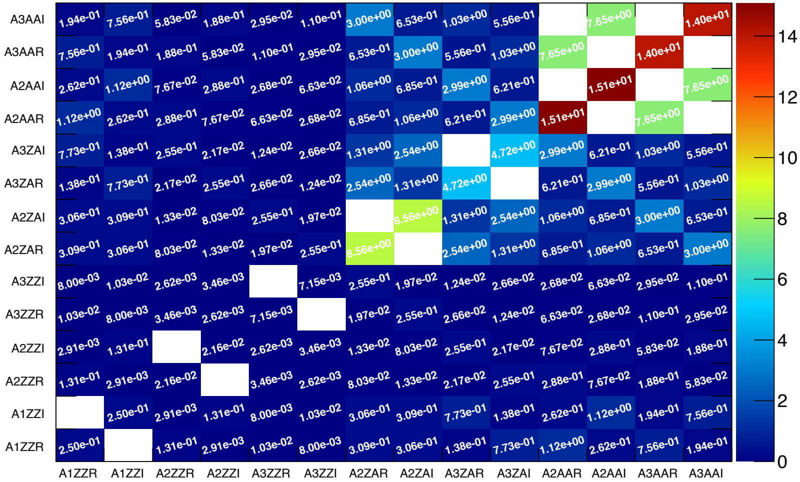
- 'Absolute branching ratios' contain some information about shape

	A1ZZR	A1ZZI	A2ZZR	A2ZZI	A3ZZR	A3ZZI	A2ZAR	A2ZAI	A3ZAR	A3ZAI	A2AAR	A2AAI	A3AAR	A3AAI
A3AAI	7.71e-02	3.78e-01	1.55e-02	3.52e-02	1.16e-02	6.97e-02	2.22e+00	5.13e-01	4.22e-02	2.21e-01		1.13e+00		2.55e+00
A3AAR	3.78e-01	7.71e-02	3.52e-02	1.55e-02	6.97e-02	1.16e-02	5.13e-01	2.22e+00	2.21e-01	4.22e-02	1.13e+00		2.55e+00	
A2AAI	1.29e-01	5.84e-01	3.32e-02	1.50e-01	1.55e-02	3.52e-02	7.27e-02	3.06e-01	2.22e+00	5.13e-01		3.00e+00		1.13e+00
A2AAR	5.84e-01	1.29e-01	1.50e-01	3.32e-02	3.52e-02	1.55e-02	3.06e-01	7.27e-02	5.13e-01	2.22e+00	3.00e+00		1.13e+00	
A3ZAI	8.34e-01	1.61e-01	3.00e-01	2.33e-02	1.09e-03	3.38e-02	1.47e+00	2.92e+00		5.38e+00	2.22e+00	5.13e-01	4.22e-02	2.21e-01
A3ZAR	1.61e-01	8.34e-01	2.33e-02	3.00e-01	3.38e-02	1.09e-03	2.92e+00	1.47e+00	5.38e+00		5.13e-01	2.22e+00	2.21e-01	4.22e-02
A2ZAI	3.67e-01	3.31e-01	3.02e-03	9.09e-02	3.00e-01	2.32e-02		9.58e+00	1.47e+00	2.92e+00	7.27e-02	3.06e-01	2.22e+00	5.13e-01
A2ZAR	3.31e-01	3.67e-01	9.09e-02	3.02e-03	2.32e-02	3.00e-01	9.58e+00		2.92e+00	1.47e+00	3.06e-01	7.27e-02	5.13e-01	2.22e+00
A3ZZI	7.90e-03	1.36e-02	3.38e-03	5.06e-03		9.16e-03	3.00e-01	2.32e-02	1.09e-03	3.38e-02	1.55e-02	3.52e-02	1.16e-02	6.97e-02
A3ZZR	1.36e-02	7.90e-03	5.06e-03	3.38e-03	9.16e-03		2.32e-02	3.00e-01	3.38e-02	1.09e-03	3.52e-02	1.55e-02	6.97e-02	1.16e-02
A2ZZI	2.82e-03	1.39e-01		2.53e-02	3.38e-03	5.06e-03	3.02e-03	9.09e-02	3.00e-01	2.33e-02	3.32e-02	1.50e-01	1.55e-02	3.52e-02
A2ZZR	1.39e-01	2.82e-03	2.53e-02		5.06e-03	3.38e-03	9.09e-02	3.02e-03	2.33e-02	3.00e-01	1.50e-01	3.32e-02	3.52e-02	1.55e-02
A1ZZI		2.50e-01	2.82e-03	1.39e-01	7.90e-03	1.36e-02	3.67e-01	3.31e-01	8.34e-01	1.61e-01	1.29e-01	5.84e-01	7.71e-02	3.78e-01
A1ZZR	2.50e-01		1.39e-01	2.82e-03	1.36e-02	7.90e-03	3.31e-01	3.67e-01	1.61e-01	8.34e-01	5.84e-01	1.29e-01	3.78e-01	7.71e-02

Preliminary

Extra Slides: 'Absolute Branching Ratios' - $4e$

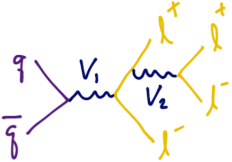
- Again differ between $2e2\mu$ and $4e/4\mu$



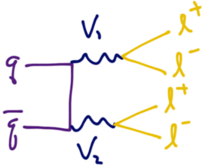
Preliminary

Extra Slides: $q\bar{q} \to 2e2\mu$ Background Components

- s-channel 4ℓ process



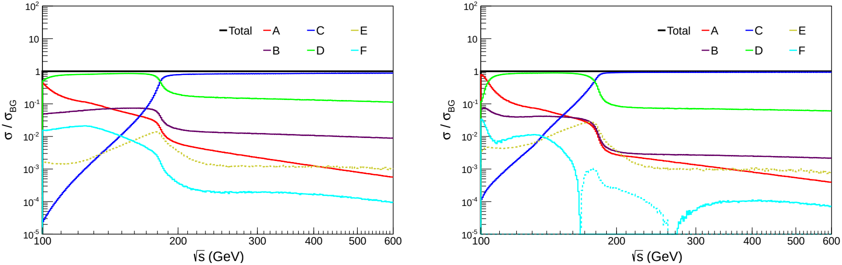
- $t + u$-channel di-boson production



- Including their interference
- The relative fraction of these components depends on s

- Left: 4 GeV$< M_{1,2} <$ 120 GeV
- Right: 40 GeV$< M_1 <$ 120 GeV and 10 GeV$< M_2 <$ 120 GeV

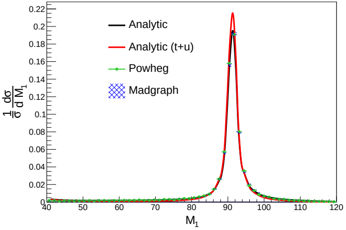
Y. Chen, N. Tran, RVM: **1211.1959**

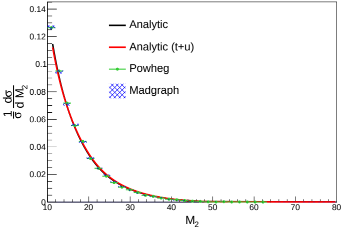


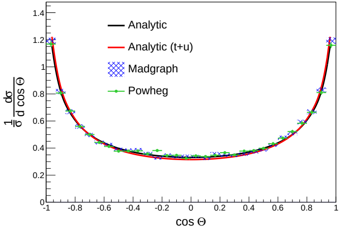
- In Higgs signal region $\sim$ 125 GeV $Z\gamma$ di-boson production dominates
- Small contribution from s-channel $Z \to 2e2\mu$ production
- Will see this can still affect angular distributions

Extra Slides: BG Validation with Madgraph/POWHEG

- Phase space: 110 GeV $\sqrt{s} < 140$ GeV with 40 GeV$< M_1 <$120 GeV and 10 GeV$< M_2 <$120 GeV

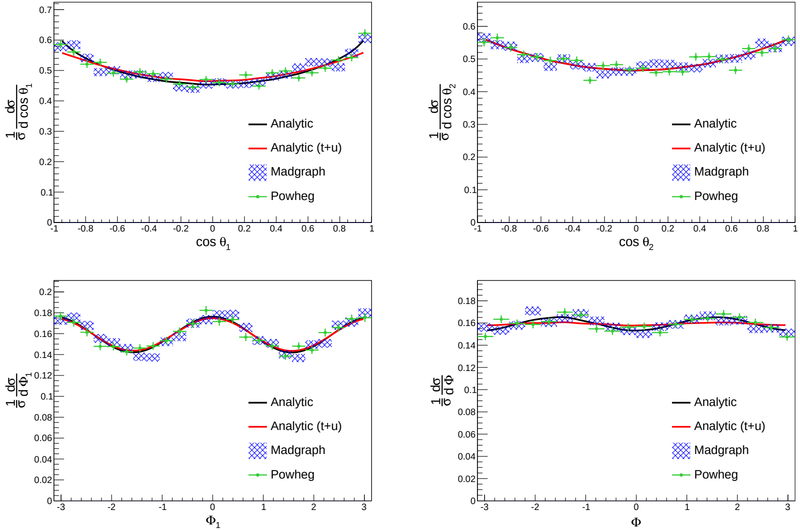




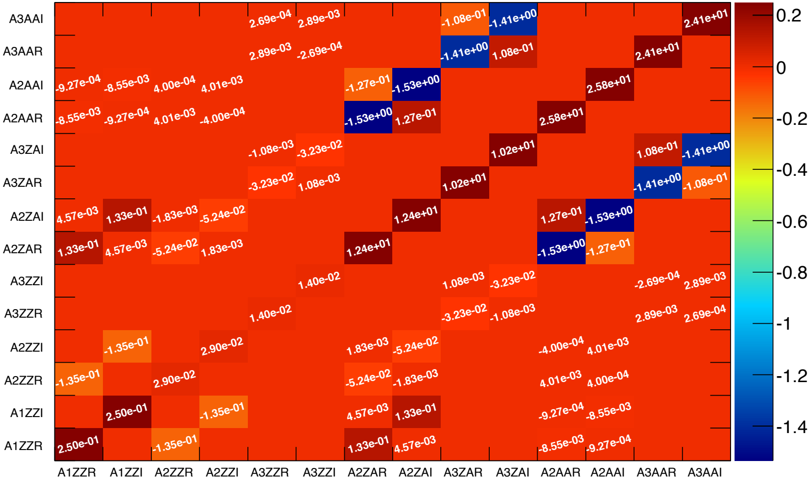


Extra Slides: BG Validation with Madgraph/POWHEG

- The lepton decay angles



- 'Branching ratios' with a Z boson 'cut out' of phase space



Preliminary

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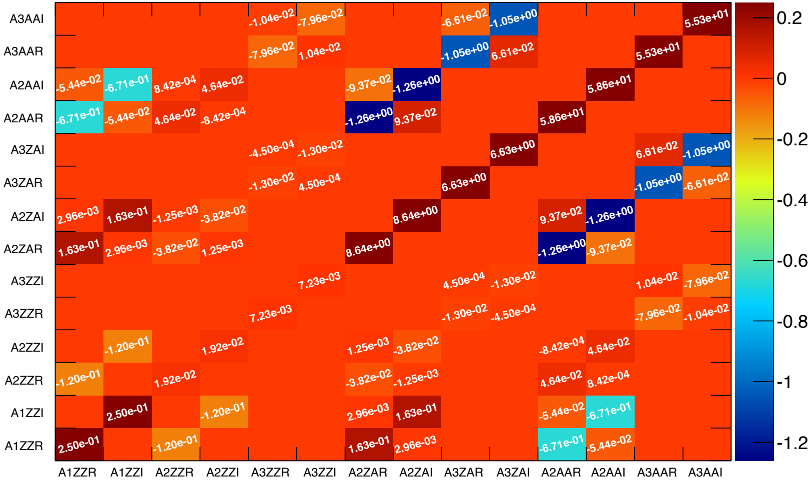

Preliminary

Extra Slides: Production Spectrum

- We need a function for the 'production' spectrum to form full pdf

$$P(s, \vec{p}_T, Y, M_1, M_2, \vec{\Omega}|\vec{\lambda}) =$$
$$\frac{d\sigma_{4\ell}(s, M_1, M_2, \vec{\Omega}|\vec{\lambda})}{dM_1^2 dM_2^2 d\vec{\Omega}} \times W_{\mathrm{prod}}(s, \vec{p}_T, Y)$$

- Several options for obtaining W_{prod}:
  - Can construct 'analytic' parametrization of parton distribution functions **(see Gao, Gritsan et. al. 1001.3396)**
  - Use 'look up' tables and boost events accordingly
  - NLO effects can be included here as well **(see Campbell, Giele, Williams)**
- Currently working on finding optimal implementation
- Since we ultimately fit to ratios of parameters as well as fractional yield, analysis largely insensitive to these 'production effects'
- Enters mainly as an acceptance effect due to detector

Extra Slides: Convolution of *pdf*

- It is a 12 dimensional integration over the components of the three momenta of the four massless final state leptons
- We can parametrize these 12 observables in the CM frame as

$$\begin{aligned} \vec{X} &= (s, \mathbf{p}_T, Y, M_1, M_2, \vec{\Omega}) \\ d\vec{X} &= ds d\mathbf{p}_T dY dM_1^2 dM_2^2 d\vec{\Omega} \end{aligned}$$

(we implicitly include angle associated with a global rotation of entire event)

- Not convenient basis for the integration so we must transform to a better basis where integration can be done
- Transform from CM frame to components of the three momenta of the four massless final state leptons ($\vec{X}^G \to \vec{P}^G$)

Extra Slides: $p_{i_{||}}$ and $\vec{p}_{i\perp}$ Basis

- We assume that detector smearing will only affect the component of the lepton momentum parallel to the direction ($p_{i_{||}}$) of motion and not the two perpendicular components ($\vec{p}_{i\perp}$)
  (Note that this is equivalent to assuming angular resolution effects due to detector smearing can be neglected)
- Now decompose the lepton three momenta $\vec{p}_i$ in terms of $p_{i_{||}}$ and $\vec{p}_{i\perp}$
- In $(p_{i_{||}}, \vec{p}_{i\perp})$ basis only transfer function associated with $p_{i_{||}}$ is non-trivial
- The transfer function for the perpendicular components can be represented simply as a delta function for each perpendicular direction
- This allows for trivial integration over the 8 variables associated with $\vec{p}_i^{\perp}$
- Of course one must include the proper Jacobian in this transformation
  see technical note for details

Extra Slides: Final Integration

- We have a 4D integration over $\prod_i^4 p_{i_{||}}$ left to to do
- Transfer functions parametrized in terms of variables $c_i = p_{i_{||}}^{\mathrm{R}} / p_{i_{||}}^{\mathrm{G}}$
- Where we have $c_1 c_2 = (M_1^{\mathrm{R}} / M_1^{\mathrm{G}})^2$ and $c_3 c_4 = (M_2^R / M_2^G)^2$
- Substitute $c_2, c_4 \to {M_1}^{\mathrm{G}} {M_2}^{\mathrm{G}}$ to obtain final basis used for integration

$$P(\vec{X}^{\mathrm{R}}) = \int P(\vec{X}^{\mathrm{G}}) T(\vec{c}\,|\vec{P}^G) \\ \times |\mathcal{J}| dc_1 dc_3 d{M_1^2}^{\mathrm{G}} d{M_2^2}^{\mathrm{G}}$$

- Where $|\mathcal{J}|$ encompasses all change of variables in intermediate steps
- This integral is manageable (with extra complication in case of signal)
- Once performed we are left with a detector level *pdf* in terms of $\vec{X}^R$

see technical note for details

Extra Slides: List of Systematics Considered

- We are treating the following systematics:
  - Harder/softer lepton energy response
  - Wider/narrower lepton energy resolution
  - Harder/softer 4l spectrum
  - Central/forward 4l spectrum
  - Wrong mass assumption for signal
  - Systematics from different choice for production spectrum
- Can implement into likelihood via nuisance parameters

$$\begin{aligned}\mathcal{P}(\mathcal{O}|n) &= (1-n)\,\mathcal{P}_0(\mathcal{O}) + n\,P_1\mathcal{O}\\ &= P_0\mathcal{O} + n\,[P_1\mathcal{O} - P_0\mathcal{O}]\end{aligned}$$

- Maximize w.r.t. to *n* for each systematic

Extra Slides: Ongoing/Future Work

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- Recent proposals by some theorists include:

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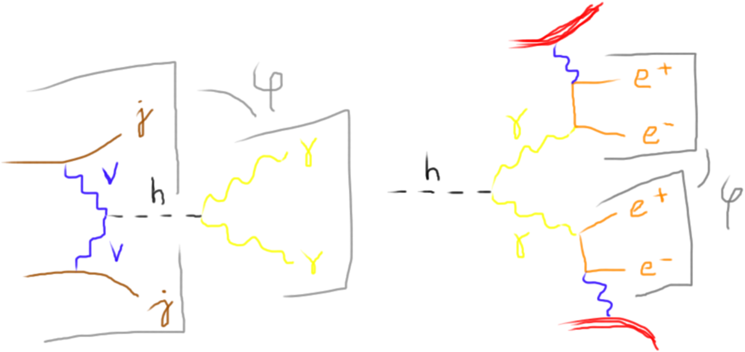
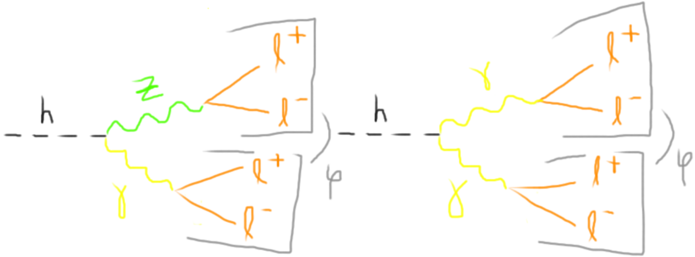
- Recent proposals by some theorists include:
  - Measuring correlations in $VBF \to \gamma\gamma$

    M. Buckley, M. Ramsey-Musolf: **1208.4840**
  - Measuring correlations between photons which convert in detector

    F. Bishara, Y. Grossman, R. Harnik, D. Robinson, J.Shu, J. Zupan: **TALK at KITP WORKSHOP**



- Other possibilities which we are working on include:
  - Extracting the $\gamma\gamma$ and $Z\gamma$ component from golden channel



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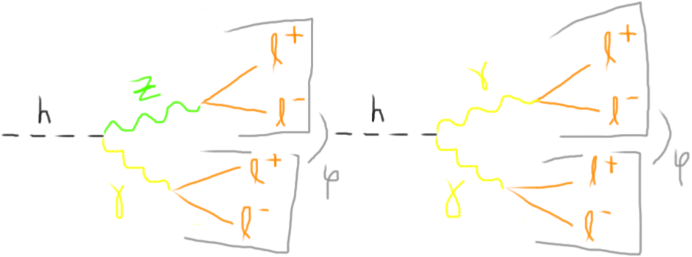

  - Studying interference in $h \to Z\gamma/\gamma\gamma \to 2\ell\gamma \propto A_2^{Z\gamma} * A_3^{\gamma\gamma} + \cdots$